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ABSTRACT

This paper reports on results of a series of three group interviews with three high school sophomores who used a motion detector to explore a mechanical device, the Bouncing Car device, that can display periodic and chaotic behaviors. The ways that students interacted with the Bouncing Car and used their body motions and imaginations to try to experience the motions the device made were observed. Observations suggest that an important contribution to student interactions with physical devices of this sort comes from their reflections on everyday bodily experience. Four episodes in the students' work with the device are described, showing the growth of a sense of complexity throughout these episodes, from their initial descriptions of behaviors obvious to them to a sense of the ways in which the Bouncing Car's behavior is fundamentally unpredictable. This development supports the notion that complexity or simplicity are not "in the device," but grow in the course of experience with the device, and that complexity is not a given, but an outcome of the active participation in the conversation about and experimentation with the tools at hand. (Contains four figures and three references.) (Author/SLD)

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ED 400 319

"This is true: that's how it is.": The Bouncing Car and the Development of Complexity

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Abstract

This paper reports on results of a series of three group interviews with three high school sophomores who explored a device, the Bouncing Car device, that can display periodic and chaotic behaviors, with the aid of a motion detector. We have observed the ways that students interacted with the Bouncing Car device and used their body motions and imaginations to try to experience the motions that the device made. Our observations suggest to us that an important contribution of students' interaction with physical devices, such as the Bouncing Cart, is their reflection on the everyday bodily experience. We describe four episodes in the students' work with the device, and the growth of their sense of complexity throughout these episodes, from their initial description of behaviors obvious to them, to a sense of the ways in which the Bouncing Car device's behavior is fundamentally unpredictable. This development supports the notion that complexity or simplicity are not "in the device" but grow in the course experience with the device, and that complexity is not a given but an outcome of the active participation in the conversation about and experimentation with the tools at hand.

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Introduction

The Project

TERC's work on the SimCalc project is part of a larger project and a larger body of work concentrating on giving more students access, from kindergarten through college, to the fundamental ideas of calculus, also known as the mathematics of change. TERC's work on SimCalc has focused on how the ideas of dynamical systems modeling can enrich students' and our own understandings of the mathematics of change. We have investigated these questions in individual interviews, group interviews, and classroom studies with high school students, and our future work will involve similar studies with elementary school students. Ideas that are important in our group's work are a fundamental respect for the learner that recognizes that each student has something to teach us, and that includes a willingness to learn new things from the student about the subject matter we are investigating together. Another important part of our work has been the acceptance that the researcher(s) and student(s) are investigating subject matter together, so that the researcher is part of the process under study, and not just an objective observer of it (Wright, 1994).

The Study

In the study we will report on in this paper, we undertook 3 approximately 90-minute interviews with a group of 3 students at their high school. The interviews were scheduled during a week of make-up work preceding a winter break, and the three students were chosen based on their availability for the same 90-minute time period (2 class periods separated by a 5-minute break). The students were all sophomores in high school at the time of the interview, and were taking Algebra I. The students are Joshua, Victor, and Terence. A fourth student, Darren, participated in the first half of the first interview, but had scheduling conflicts that prevented him from attending any others. We plan to interview some young women in future interviews, but were not able to interview any young women at this time because of scheduling difficulties. Tracy Noble was the interviewer for all three interviews, and Joe Cook, a teacher at another school, and researcher with the group, attended part of the first interview, and participated in the discussion. Nicole Zubrovski operated two cameras throughout the three interviews. For each interview, the general view was taped using one camera, and the computer screen using another. The two views were mixed to create one tape for analysis. These tapes were then analyzed by the group, and partially transcribed.

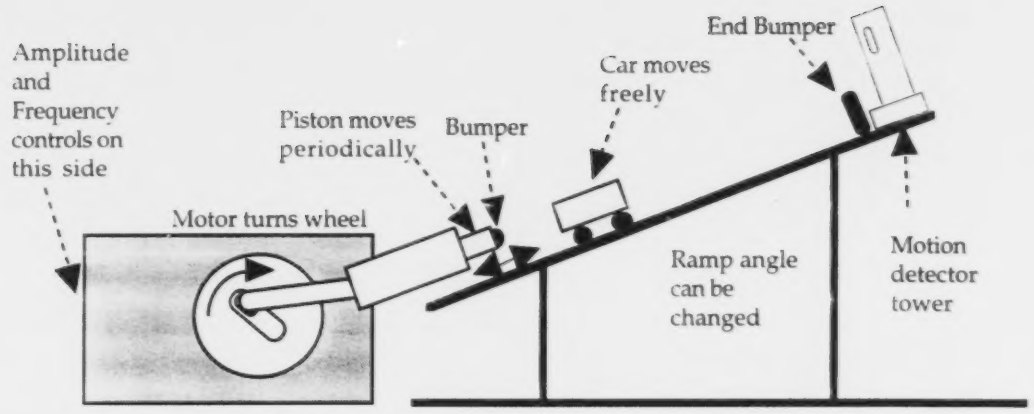
As mentioned earlier, the researchers, in this case Tracy and Joe, were not objective observers assumed to have no influence on the interview situation. As we will see in the transcript, Tracy and Joe were also learning new things about the device that the group worked with, and asking their own questions about it, in addition to asking the students about their thinking. Thus, in our description of the events in the

interviews, when we refer to the group, we refer to the students and to Tracy (and in the first interview, Joe as well). When an idea is developed in the interviews by some of the students in conjunction with Tracy, we have tried to explicitly describe the process. We don't see this as a cause for concern, but instead an opportunity to recognize and understand the role the interviewer plays in any given interaction (Wright, 1994).

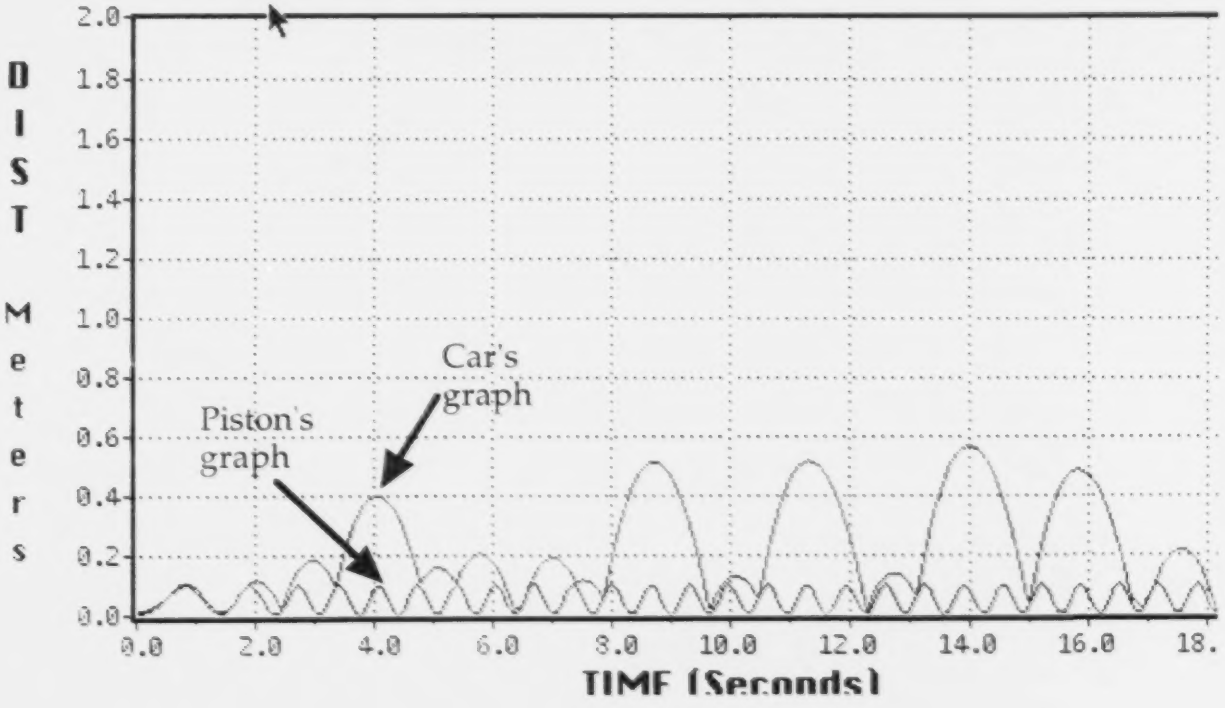
The Device and Software

The Bouncing Car device was developed as an example of one of the conceptually simple mechanisms that can produce both periodic and chaotic behavior. It was designed by Arthur Ganson and members of the research group and built by Arthur Ganson. It is an analog to the bouncing ball system, which has been analyzed in some detail by physicists (Tufillaro, Abbott, and Reilly, 1992; Tufillaro and Albano, 1986; and Mello and Tufillaro, 1987). The bouncing ball system consists of a small ball, such as a ball bearing, that is bounced up and down on top of a vibrating speaker. Each time the ball is bounced up into the air, its velocity after impact determines the time it takes the ball to travel through the air and land on the speaker again, which determines what speed the speaker will be traveling when the ball hits it, which determines how the ball will bounce the next time. This is the origin of the non-linearity of this model, similar to the non-linearity of the forced pendulum, for instance, a pushed swing. Small changes in the ball's motion can be compounded over time as the ball interacts will the oscillating speaker, causing the sensitive dependence on initial conditions characteristic of non-linear systems. The Bouncing Car device is an analog of this device, in that it consists of a freely moving object that is periodically forced. The Bouncing Car device is like the bouncing ball system turned on its side, with a motor driving a piston that moves periodically and interacts with a car that can bounce against it and move up and down an inclined track. Since the car rolls up and down an incline, experiencing a smaller acceleration due to gravity than the bouncing ball does, the motion of the car is more easily observable than that of the bouncing ball.

A schematic diagram of the device is shown below. The amplitude and frequency of the piston's motion can be adjusted during its motion or while the device is off. Much of the device is made of transparent Plexiglas so that students can see its inner workings.



The Bouncing Car device is hooked up to a motion detector that reads the location of both the piston and the car. The motion detector is manufactured by Lipmann Electronics, in Israel, and works by having a "tower" detector [See figure above] detect the positions of 2 "button" sensors, distinguished by color, one mounted on the car and the other on the piston. The software, developed by Walter Lenk and members of our research group displays graphs of position vs. time for the piston and the car in real time, displayed in the color of the button sensor providing the signal. The software can also display velocity and acceleration in real time, along either axis. A sample graph of position vs. time for the piston and the car is shown below:



The top graph is the graph of the car's motion, and the bottom one describes the piston's motion. The two graphs show up on the computer screen in two different colors, such as red and blue, depending on which sensor button is affixed to which object.

Themes

Interaction with Physical Device

There is a large body of research in mathematics and science education regarding physical objects, devices, etc., as part of learning environments, inside and outside of school, and the use of manipulatives or experimental apparatus is seen as essential in many math and science classrooms. In our own work with students in interview and classroom settings, we have invariably used physical devices, and often MBL devices as a large part of the work of the interview. In this paper, we would like to explore the nature of the students' and researchers' interaction with the physical device they are using, in this case, the Bouncing Car. We would like to understand more about how students make use of physical objects and tools presented to them as part of a learning environment, and what other parts of the learning environment help them to make use of the tools. One consistent pattern we have found is students' use of gestures analogous to the motions of the device. Translating the device's motion into their own body motions was a way for them to experience "being" the device in order to understand it better. We have also seen the students use both gestures and talk to make connection between the device and their experiences.

Complexity

In order to think about how the students might experience complexity in their work with the Bouncing Car, we need to specify what we mean by "complexity". In everyday life, if we say that something is "complex", we may mean that: 1) we don't understand what is going on, 2) there is so much going on or so many different things going on that we cannot keep track of them all; or 3) there are so many different ways to think about this, so many different interpretations, that we experience it as complex. In thinking about curriculum topics, it is not uncommon to hear talk about some subjects, experiments, or devices, being "too simple" for one grade, or "too complicated" for another. We would like to argue that in any physical system (or mathematical problem, curriculum topic, etc..) there is the potential to find complexity. In these interviews, we see the group's sense of the complexity of the device developing over time, through their interaction with the device and with each other. The quality of complexity does not reside in the device itself, and is not something immediately apprehended by the group. Instead, they have an extended conversation with the device and with each other, which leads the group to a sense that there are many things

going on in the Bouncing Car's behavior, and that there are many viewpoints from which to understand it.

Of course, we believe not only that it is possible to find complexity in many places, but also that it is worthwhile to allow it to develop in learning situations, and to explore it. Along with Duckworth (1991), we feel that complexity is often what makes a topic interesting, and allows multiple ways for learners to connect with a topic. There may, of course, be experiences of complexity where we feel that something is just "too complex," and thus overwhelming. This kind of experience may cause us to give up before we have started exploring this overly complex thing. We suggest that an important component of a situation that is experienced as complex but not too complex is the availability of multiple entry points, and thus multiple ways to begin to explore the situation that involve things that we understand or are familiar with. The students in this study chose to begin their exploration of the device by describing the way the car responded to collisions with the piston. To them, the rule they found was obvious, and easy to understand in terms of things hitting other things, something they seemed familiar with. One role a physical device can play in a learning situation is to provide these kinds of entry points, if the students can use what they know of other physical experiences to begin to understand the device.

The Interviews

Overall Story of the 3 Interviews

In the 1st interview, the students began working with the Bouncing Car device for the first time, and explored some of the things they could predict about the car's motion with the piston moving and with the piston stationary. Episode 1 involves one of the first rules that the students describe about the car's motion. About 20 minutes into the interview, Tracy introduced the motion detector to the group and the group began making graphs of the car and piston's motion, which lead to making and testing some new predictions about the car' motion. The effect of the weight added to the car on the way it bounces against a stationary piston was particularly interesting to the group, and Episode 2 consists of their discussion of their predictions about the effect of changing the weight on the car. At the end of this session, they made a plan to continue experimenting with this idea during the second session, by adding even more weight to the car.

The 2nd interview begins with the group planning to add much more weight to the car and graphing it's bounces against a stationary piston. The additional weight apparently made the car unbalanced, and with many repeated trials the group found that the wheels of the car kept coming out of their grooves, which made it impossible to collect good data for the heavily-weighted car. Next the group began exploring the effect of changing the ramp's angle on the car's bouncing against the stationary piston, another idea that had been mentioned in the first interview. During this exploration, one of the students chose the software option of displaying first the velocity vs. time

graph, and later the velocity vs. distance graph, and when each new type of graph was made, the students spent some time finding ways to interpret the new graph. Episode 3 consists of one of the group's first discussions of velocity vs. distance graphs.

The 3rd interview begins with Tracy posing a challenge to the students: to adjust the device so that the piston is moving and the car bounces against it periodically, bouncing up to the same height every time. The students claim that this is impossible, and explain why. Then they experiment with the device and try to find patterns in the aperiodic motions of the car that they cause. After their break, Tracy hands out ball-and-paddle toys and asks the students if they can make the regular motion she has described with these toys.

After experimenting with the toys for a while, the students return to the device and make some additional attempts to make the car move periodically, while describing why it is impossible, and occasionally referring back to the ball-and-paddle toys. Episode 4 consists of part of this discussion, and then the event of one student finally releasing the car in such a way as to produce a periodic motion.

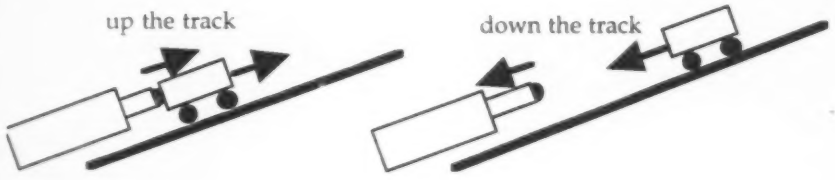
Toward Episode 1

Notation:

.....	represents the voice trailing off
. . .	represents omitted transcript
/word/	represents overlapping speech
word]	represents interrupted speech
//word	represents interrupting speech

deleted transcript and events, when they are substantial, will be summarized in italics like this, within the transcript

When directions of motion of the car and piston are referred to in the transcript, "up" or "up the track" and "down" or "down the track" are the two directions of motion that the car or the piston can have, and these are indicated in the drawing below:



Before Episode 1

Tracy and the students discussed what the device is and how the students expected it to move. Two students recognized part of the device as a piston. When Tracy turned on the device, the car was resting on the piston, and moving with it. The group predicted that when the speed of the piston was turned up, the car would start bouncing away from the piston, and they experimented to show this. Then they try turning the amplitude up all the way, and the frequency up all the way, trying to get the car to hit the end bumper at the top of the track this is a common desire among students and adults we have seen use this device]. Tracy suggests that they look for what they car predict about how the car moves, and Joshua's prediction begins Episode 1.

Summary of Episode 1

The group discusses what makes the car bounce up high, away from the piston. The initial idea Joshua introduces is developed in the course of this interview into a statement about how the car's bounce height is determined by the way the piston is moving when the car hits it.

Episode 1 - Interview 1 (12:23 - 18:30 minutes)
What Determines How High the Car Bounces?

Annotated Transcript

Joshua: It [*car*] only moves when it [*piston*] hits it [*gestures 2 fists hitting each other*], because when it [*piston*] pushes it [*moves right hand*], it doesn't send it [*car*] anywhere.

Comment: We have come to interpret this statement to mean that when the car is resting on the piston and the piston moves back and forth, the piston "doesn't send" the car anywhere, doesn't make the car move away from it, up the track. But when the car and piston are both moving and then hit each other, then the car "moves" up the track. Joshua elaborates on this idea below:

. . .

Joshua: This part right here [*pointing at the piston*], it doesn't send it [*car*] any where when it's pushing it [*car*] [*moves finger up the track to indicate the piston pushing the car upward*], only when it [*car*] comes back down, [*gestures left hand coming down the track, like the car, and right hand coming up the track, like the piston, and the two hands hitting each other*] and it [*piston*] comes out [?] at the same time.

Joshua clarifies a bit more, in response to Tracy's questions, then Tracy asks him how he could show what he describes, using the device itself. Joshua describes how he could demonstrate this, and then attempts to demonstrate it using the device. Joshua and Victor both clarify further. Then Tracy asks Terence, Victor, and Darren what they think of what Joshua said.

Victor: Yeah, it's, I think it mostly is the, the contac-- like when both of them are coming at [?] together [*brings two hands together*] and they make a stronger force and bounce [*brings hands together and apart*] and it [*car*] goes to the top [*of the track*].

Comment: Victor clarifies the importance of coming together and bouncing for making the car move high up the track. He also mentions that the piston and the car should be moving towards each other to "make a stronger force" and make the car bounce high. We will see how the piston's motion becomes a more central part of this discussion shortly, as Tracy picks up on the idea.

Tracy: So, when both of them [*car and piston*] are coming together [*brings hands together*].

Darren: Um hm.

Victor: Yeah.

Tracy: So, so it's partly that it's boun- that it's hitting it [*hits one hand with the other a few times*], but it's also that- does it also depend on how the piston is moving [*moves hand back and forth, like the piston*]?

Terence: Yeah, if it's moving, like, all the way up [*gestures up the track*], like if this is coming down like this [*gestures down the track*] and this is coming down [*gestures coming down the track*], it [*car*] wouldn't go far. Like if this [*piston*] goes up [*moves hand up the track*] and then this [*car*] comes down [*moves hand down track*], they hit each other [*hits hands together*], and that makes it [*car*] go farther. [Tracy: It would go farther?] Um hm.

Comment: Terence clarifies the relation between bounce height and the motion of the piston here. He explains that if the piston and the car are both moving down the track when the impact occurs, the car "wouldn't go far" back up the track. But if the piston is moving up the track while the car is moving down the track, towards the piston, the impact causes the car to move up farther.

Tracy: What do you think of that, Darren?

Darren: This is true: that's how it is.

Comment: There are two ways to read Darren's comment here. One is as an evasive move, to avoid having to explain something to Tracy. Another way to interpret this is as an expression of Darren's feeling that the phenomenon Terence has described is simply self-evident, and needs no further explanation. We will see further examples of the sense that this phenomenon is simply self-evident in the remainder of this episode.

Tracy: [laughs] That's just how it is. Cou- how could we show that? What do you think, Darren?

Victor turns on the machine, and the piston starts moving, at low frequency and amplitude. Darren, who had done work the previous year with the motion detector, suggests using the motion detector to demonstrate the phenomenon Joshua, Victor, and Terence have described. Tracy asks Darren to demonstrate it without the motion detector first. Darren attempts to demonstrate this, but Terence finds his demonstration unclear. Tracy then asks Terence to demonstrate the phenomenon himself.

Terence: Say, say if there was, like, right there [*moving the car a little away from the piston*] and [*moves the car down to hit the piston*] they were both -- hold on. Say, like [*moves car away from piston again*], when it comes down [*moves car down to meet piston*] like that, it [*car*] ain't gonna go far [*moves car back up track, away from piston*]. The only way like it will go far is if it [*car*] comes down like that [*drops car so that it falls and hits piston, bouncing*], when this one [*piston*] pushes up [*gesturing upward with left hand*], and this one comes down [*moving the car toward the piston with right hand*], like that [*moves the car and the hand toward each other*], but if this one [*piston*] is moved back [*moves left hand down the track, away from the car, to indicate piston moving down*] then this one [*car*] comes down [*moves car down track with right hand*], then it [*piston*] won't push it [*car*] all the way [*up the track*].

Joshua attempts to demonstrate what he means as well, by carefully timing his drops of the car against the piston, so that the car will hit the piston just at the point he wants. Joshua describes how the car bounces differently depending on when it hits the piston. He clarifies that it is the direction of motion of the piston, and not the location of the piston that affects how high the car bounces. Tracy asks why this happens, and there is no response for a few seconds, until Victor responds:

Victor: If it's moving forward at a fast speed [*the piston is moving upward fast*], and this [*car*] is coming down right at the time it's moving forward [*the piston is moving upward*], it'll [*the car will*] bounce more [*higher*], but if it's moving backwards [*the piston is moving down*], and this [*car*] is coming down right.. and it's gonna make contact [*with the piston*] while the piston's moving backwards [*down*], it's not gonna bounce as much [*the car won't bounce as high*] as if it [*the piston*] was going up, and [*the car was*] coming down right at it [*the piston*].

When Tracy questions Victor and the group further about why this is true, Victor becomes apparently frustrated, responding:

Victor: A stronger, the force [*of the piston*] is coming right at it [*hits hand with fist*] and it [*piston*] bounces it [*car*], and.... Yeah.

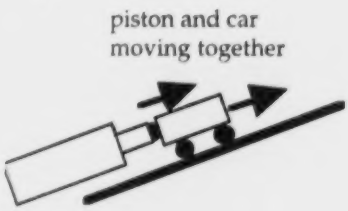
Tracy: All right.

Interpretive Notes

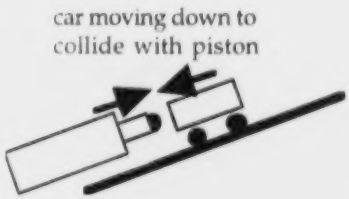
• What is Going On?

The question the group seems to be grappling with is what makes the car bounce up high or low when it hits the piston. In Joshua's initial explanation, it sounds like he's

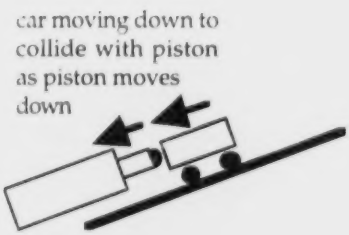
making the distinction between the way the piston pushes the car up when the car is just resting on it:



and the way the piston makes the car move when the car collides with it:



This idea is developed by the group into a statement about when the car's collision with the bumper will produce a high bounce and when it will produce a low bounce. They decide that a high bounce is produced when the car comes down and hits the piston just as the piston is coming up towards the car [picture]. A low bounce is produced when the piston is moving down, away from the car, as the car comes down to hit it:



This rule could be expressed in terms of the conservation of momentum in a collision, given that when the piston is moving upward at the time of the collision, there is more upward momentum available to impart to the car than when the piston is moving downwards at the time of the collision. This discussion is complicated, of course, by the question of whether the piston experiences any recoil from the collision and how much recoil, but the basic description is still valid.

• The Interaction with the Physical Device

These students seem to be sure that if the piston comes towards the car fast, the car will bounce back high, and they see no need for further explanation. What allows them to

gain this sense of certainty? Three of the students and Tracy repeatedly use a technique of describing the car and piston motions by using one or both hands to move as the piston and/or the car, to experience being the piston and/or the car. The first example in this episode occurs when Joshua states: "It [*car*] only moves when it [*piston*] hits it [*gestures 2 fists hitting each other*]." He's not only using his two fists to represent the car and the piston, but also to experience *being* the car and the piston during a collision, so that he actually feels what an impact is like. Victor uses his hands similarly when he explains: "like when both of them [*car and piston*] are coming at [?] together [*brings two hands together*] and they make a stronger force and bounce [*brings hands together and apart*] and it [*car*] goes to the top [*of the track*]." Tracy gestures similarly in asking for more explanation about this: "so it's partly that it's boun- that it's hitting it [*hits one hand with the other a few times*],". Then Terence explains further: "Like if this [*piston*] goes up [*moves hand up the track*] and then this [*car*] comes down [*moves hand down track*], they hit each other [*hits hands together*] and that makes it [*car*] go farther." Terence experiences the motion of the car and the piston, and, finally, their hitting each other, by moving his hands the way he imagines the car and piston may move.

This mode of interacting with the device by trying to be the device is something we saw these students and Tracy do throughout these three interviews, and it is something that we noticed in our work with both high school and elementary school students in other studies. In this case, moving their hands to be the car and the piston seemed to allow these students to make a connection to strong physical intuitions about motions. We postulate that this may be part of the reason they were so convinced that when the piston is moving towards the car at the time of impact, the bounce of the car will be higher than when the piston is moving away at the time of impact; they could feel it in their hands.

- **Complexity**

How do these students experience the device's motion in this episode? Does it seem complex to them? Joshua's first description of how the car and piston interact seems simple: "It [*car*] only moves when it [*piston*] hits it [*gestures 2 fists hitting each other*], because when it [*piston*] pushes it [*moves right hand leftwards*], it doesn't send it [*car*] anywhere." Yet it requires a great deal of elaboration and clarification by the whole group in order to make it clear. In this process, the students do not appear to have the sense that they don't understand how the device works, or that there is too much going on in it or too many different ways to interpret what is going on. Instead, they seem to feel that the way the car responds to different kinds of impacts with the piston is obvious, and doesn't need all the explanation Tracy keeps asking for.

Toward Episode 2

After a little more discussion, Tracy introduced the students to the motion detector, and they began looking at graph of position vs. velocity for the car and the piston. After the group had spent a few minutes trying to interpret the graph, Tracy asked if they could see the effect of the motion of the piston at the time of the collision on the bounce

height of the car. Victor responded immediately and accurately located the high and low bounces corresponding to hits when the piston was moving upward and downward, respectively. Next, the group began investigating how many times the car bounces when it hits a stationary piston. They do a number of trials to investigate this, and find that sometimes one of the car's back wheels comes out of the groove on the track, affecting the size of the peaks in the graphs. Victor proposes a solution to this problem: he wants to add a weight to the back of the car, perhaps to hold the back wheels down. This initiates a discussion of the effect of added weight on the car's bounce height. Before Episode 2 begins, the first period of the interview ends, and Darren leaves the group.

Summary of Episode 2

In Episode 2, Joshua and Victor each articulate their theories about the effect of adding weight to the car on the way the car bounces against a stationary piston. Each of them is considering a different effect produced by the weight. Terence says that he believes both theories, and the group decides to try it out to see what happens.

Episode 2 -Interview 1 (53:00 - 56:00 minutes)
What Effect does Weight on Car have on Bounce Height?

Annotated Transcript

It is important to remember that the device is OFF at this time, and the experiments are all done with a car hitting a STATIONARY piston.

Joshua: I think, like, the heavier the weight is [*inaud.*] the more it'll, it'll move up [*the car will bounce back up the track*]. [Tracy: The more it'll move...] 'Cause it'll [*the car will*] get more speed on the way down.

Comment: Joshua describes his belief that a heavier car would have a greater acceleration, and "get more speed" as it falls down the track.

Tracy: [*pointing to the track*] So you mean if, if we made the car heavier, it would move up [*moving hand up the track*] more [*after a bounce*]?

Joshua: Yeah, it would be faster.

Tracy: OK, I have to write some of this down. I'm getting confused. So, one of the things we want to try...

. . .

Victor: . . . -the peaks [*on a position vs. time graph of the car's motion*] will be smaller.

Comment: Victor uses language that describes the position vs. time graph to give his prediction about the effect of weight on the way the car bounces, even though Joshua has given his prediction in terms of the speed of the car. If the peaks in the graph are smaller, that means that the car doesn't bounce up as high, which seems to be in conflict with a suggestion that the car comes down the track faster. The debate continues without any apparent difficulty in using these two very different descriptions to make apparently opposing predictions.

Tracy: Wait, so...

Joshua: If something, you know how like when people get on a sled, the more people, the faster it goes?

Comment: The analogy of the sled serves not only to support Joshua's argument, but is also a way for Joshua to put himself in the position of the car or the weight on the car, to imagine traveling down a hill in the car with extra weight on it.

Victor: But the peaks would be smaller [*on a position vs. time graph of the car's motion*], because, it'd be heavier [*the car would be*]: it [*car*] wouldn't go up that far [*after a bounce*].

Tracy: So if it's heavier [*the car*], you think [*pointing to Victor*], Victor thinks that the peaks would be smaller [*writing in her notebook*]. [Victor: Yeah.] and Joshua thinks that the peaks would be larger, and Terence thinks?

Comment: Tracy has translated Joshua's prediction into one about the peak size, as if coming down the track faster means that the car will bounce up higher. At the time, Tracy saw these descriptions as identical, and the students seem to understand what she means. We will see how this plays out shortly.

Terence: Smaller.

Tracy: Oh, Terence thinks smaller, OK. And, and [to Joshua] you're saying because if you're with more people on a sled, it goes down faster. [Joshua: Yes.] And [to Victor] you're saying... Why do you think they'd be smaller [*the peaks*]?

Victor: Because when it bounce [*brings car down the track to touch the bumper, and then moves it a little back up, as if the car bounces off the bumper*], I don't -- it would be heavier, and ...

Terence: For it to push up [*moves hand up the track, as if pushing the car*] it, [Victor: Yeah.] there's so many weight on it.

Tracy: There's so much weight on it that it would be harder [Terence: Yeah.] to push up? [Victor: Yeah.] OK, so d-

Comment: Victor, Terence, and Tracy have constructed an explanation together here. When Victor seems stuck, Terence begins gesturing with his hand playing the role of the piston pushing the car, and Tracy suggests language to describe what she thinks Terence and Victor are trying to say: "it would be harder [Terence: Yeah.] to push up?"

Joshua: //But then, then you'd have all that extra speed.

Tracy: Oh, and Joshua's saying on the way down [*gestures with 2 hands moving down the track*], you'd get extra speed, and you're [to Terence] saying on the way up [*gestures up the track with 2 hands*] it would be harder to push that weight up. [Terence:/Yeah./] [Victor:/Yeah./] So...

Victor: I, I, I would say it's, it's /it's it won't-/ [Joshua:/I don't know!/] [Tracy and Joshua and Terence laugh at the situation] it won't go faster, but it'll have more momentum, so maybe there's some truth in what he [Joshua] says, but...

. . .

Terence: I go for both, I think. [Tracy: You go for both?]

Joe: But he /says it won't go faster/...

Tracy: /It's both smaller and/ larger?

Terence: /Because, it's l-/ (pause) I don't know, 'cause, like, it is true, like, the, the more weight you put on it [*pointing to car*], the quicker it'll come down [*moves hand down the track*], so like the quicker it comes down [*moves hand down the track, to the bumper*], the higher it should go up [*moves hand up the track*].

. . .

Victor: It won't come down quicker.

Terence: And, and , and I think it [*the peaks on the graph*] will be smaller, 'cause the more weight you have on it [*the car*], like, the less it will, like, go up.

Joshua: They might counter each other.

Tracy: [to Joshua] So they might counter each other. So, [to Terence] then what would happen? It [*the graph*] would just be the same?

Terence: /Yeah/

Victor: /No!/ [Tracy: No?] So, can't be the same. [Tracy: Can't be the same.] Cause, how it is it gonna fall faster [*moving car down the track*] when a bowling ball and a little baseball falls to earth the same way...[*inaud.*]

Tracy: Yeah, that's what I was gonna ask about, 'cause you [Victor] said it /won't fall faster [*hand gesture down track*]/

Joshua: /No, but not in the air./ [Victor: No.] [*inaud.*] *on* something.

Victor: Still the same thing [*pointing to track*]. Gravity's gravity; gravity's down.

Terence: We should just try it.

Summary of remainder of interview

After a brief period of experimentation with the effect of the height along the track from which the car is released, the group takes some data with extra weight on the car. At first it appears that the new peaks are shorter, and perhaps thinner, but then they realize that they are comparing the wrong pairs of peaks, and that in fact the heavier car had peaks of a size similar to those of the lighter car. They decide to look at the velocity vs. time graph also, and find that there is no difference in this graph for the two different weights of the car they have tried. Joshua concludes that the two effects, one increasing the speed of the car on the way down, and the other decreasing the speed of the car on the way back up, probably counter each other, and Victor suggests putting even more weight on the car at the next interview, to try to get some effect.

Interpretive notes

• What is Going On?

In Joshua's argument, he relies mainly on an analogy with his experience of a sled with more people on it traveling down a hill faster than a lighter sled. When Victor argues that a bowling ball and a baseball would fall to earth "the same way", Joshua counters that that is in the air, and that the car on the track is "*on* something," so it should behave differently than Victor's bowling ball and baseball falling in the air. Joshua's prediction seems to be based on an idea about how objects slide on surfaces. The weight of an object is directly proportional to the amount of frictional force opposing it's motion down an incline. So, does a sled move downhill faster with more people on it? Could more pressure from the weight of the people flatten or melt some snow directly under the sled, making a slipperier ride?

When Victor and Terence and Tracy describe why the Position vs. Time graph peaks would be smaller, they seem to attribute this to the bumper on the end of the piston being unable to bounce a larger mass back upward as much as a smaller mass would be bounced. This could be explained as the bumper having a diminished coefficient of restitution for very large masses, or perhaps as the piston having some recoil for very large masses, which would absorb some of the incoming momentum of the car. Either of these might occur in some circumstances, although in this case, when an additional weight was added to the car, repeated experiment finally lead to the conclusion that the peaks were the same height as they had been for the lighter car.

In addition to arguing for his own view, Victor seems convinced that Joshua's argument about the larger mass causing the car to move down faster is false. He seems certain that gravity will affect the car the same way, no matter what it's mass, and in spite of the fact that the car is rolling on a surface, as opposed to falling in the air, because: "[g]ravity's gravity." Yet for Joshua, the car rolling down an incline and balls falling in the air are very different things.

Their experiments, in which they found peaks (in position vs. time) of the same size as for the lighter car, and no change in the velocity vs. time graph either, was not seen by the students as conclusive. Joshua suggested that the two effects might have

countered each other to produce the position vs. time peaks of the same height. If that were the case, though, the velocity vs. time graphs would not be identical for the two different car weights, but would show larger negative peaks on the way down, and smaller positive peaks on the way up. In fact, the peaks all overlapped with those for the lighter car. Unfortunately, the interview ended immediately after the velocity vs. time graph was produced, and this line of reasoning was not explored. Victor's suggestion that more mass might make more of a difference makes a little more sense, because this change in mass (the addition of 1 battery to the car's top) was fairly small, and produced no observable effect. Much of the third interview was spent attempting to experiment with larger masses attached to the car. However, this tried the limits of the apparatus, as the car's wheels kept coming out of their grooves for the weighed-down car, and conclusive evidence was not found. This would have been a good time to make use of a simulation of the device if one existed.

• The Interaction with the Physical Device

Both Joshua's argument and Victor and Terence's argument about how the car will behave, depend strongly on putting themselves in the position of the piston or the car. Joshua's analogy with people on a sled: "you know how like when people get on a sled, the more people, the faster it goes?" is not just any analogy, but one which allows Joshua, and any listener who has been on a sled, to imagine the experience of traveling down a hill with extra weight on the sled. This imagined experience is a very convincing argument for Joshua's claim, and provides a new way to experience *being* the car or riding on the car in order to understand how it will behave.

The description of the heavier sled, or the bowling ball and the baseball, are also useful to these students because they refer to their own experiences with physical objects that other members of the group can relate to. Their ability to make connections between the physical device in front of them and other common experiences allows them to make strong arguments for their predictions.

Victor seems certain at the beginning of this episode that the peaks made by the car on a position vs. time graph will be smaller if the car has more weight on it, and doesn't provide much more explanation about why. But as Terence tries to help Victor, he moves his hand as if it were the piston pushing the car up:

Victor: . . . I don't -- it would be heavier, and ...

Terence: For it to push up [*moves hand up the track, as if pushing the car*] it, [Victor: Yeah.] there's so many weight on it.

Terence's motion of his hand and attempt at explanation suggest that he's trying to put himself in the position of the piston or the bumper, which has to push back upwards a very heavy weight that has just fallen on it. Tracy interprets Victor and Terence's attempts as indicating that: "There's so much weight on it [*the car*] that it would be harder to push up." From this perspective, their argument is convincing. So, how can we determine what will happen?

• **Complexity**

An apparently simple change in the weight on the car leads into an investigation that becomes more and more complex as the discussion progresses. No one in the group seems to experience the situation as complex in the sense of "I don't understand what's going on." Yet there seems to be a growing sense among the group of: "There is so much going on or so many different things going on that I cannot keep track of them all." and "There are so many different ways to think about this, so many different interpretations, that I experience it as complex." Towards the end of this episode, the group struggles to make sense of the two competing descriptions of what will happen when more weight is added to the car. Victor begins to see "some truth" in Joshua's argument: Victor: "it won't go faster, but it'll have more momentum, so maybe there's some truth in what he [Joshua] says, but..." Terence announces that he believes both interpretations, which seem to lead to conflicting outcomes:

Terence: I go for both, I think.

. . .

Tracy: It's [*the peaks are*] both smaller and larger?

Joshua suggests shortly thereafter that the two effects he and Victor describe might "counter each other", leading, presumably, to no change in peak size. More and more factors have come under consideration, and some of the group members are trying to consider two apparently competing claims at once. Soon after the utterances above, Terence suggests a way to make sense of this complexity: "[w]e should just try it," an extremely sensible idea. For the group, the situation became experienced as complex as they attempted to listen to each other's explanations, clarify what they meant, and interact with the device itself. The complexity was not inherent in the device itself, or in changing the car's mass, but in the emerging situation in which the group talked together and considered alternative points of view and new factors that might affect the behavior of the car.

Toward Episode 3

The 2nd interview begins with the group planning to add much more weight to the car and graphing it's bounces against a stationary piston. The additional weight apparently made the car unbalanced, and with many repeated trials the group found that the wheels of the car kept coming out of their grooves, which made it impossible to collect good data for the heavily-weighted car. Next the group began exploring the effect of changing the ramp's angle on the car's bouncing against the stationary piston, another idea that had been mentioned in the first interview. During this exploration, one of the students chose the software option of displaying first the velocity vs. time graph, and later the velocity vs. distance graph, and when each new type of graph was made, the students spent some time finding ways to interpret the new graph. Episode 3 consists of one of the group's first discussions of velocity vs. distance graphs.

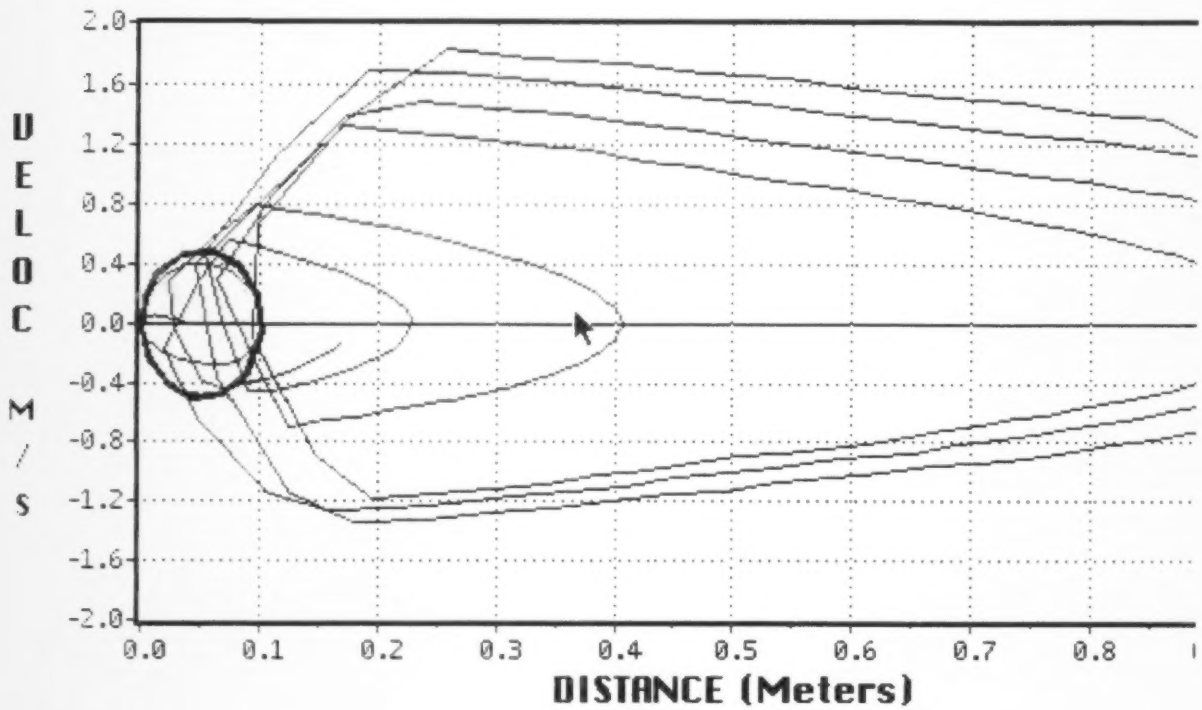
Summary of Episode 3

In Episode 3, Joshua and Victor discuss the velocity vs. distance graph that has just been produced, referring only to the circular graph produced by the button sensor attached to the piston. The piston's velocity vs. distance graph is approximately circular because it's back and forth motion in space becomes a back and forth motion in the graph, since distance is represented on the horizontal axis. The positive velocity of the forward motion gives the top half of the circle it's height, and the negative velocity during the backward motion becomes the bottom half. We refer to locations on the circle using the language of locations on a clock face.

Episode 3 - Interview 2 (1:05:50-1:06:30)
"Why is there a circle [on the graph]?"

Annotated Transcript

A graph very much like the one the group was working with is shown below. The circle on the left is the graph of the piston's motion, and the larger, bullet-shaped figures are graphs of a number of bounces of the car.



Tracy: So what did you guys think about this one [*this graph*]? This is another one [*graph*] that is different.

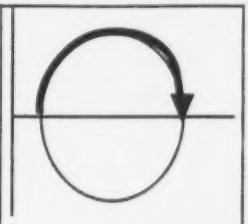
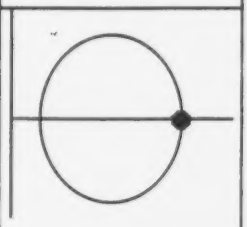
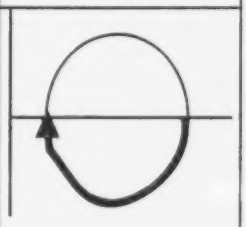
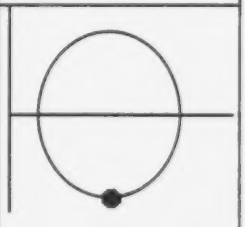
Joshua: Why is there a circle [*on the graph*]? There's something circular?

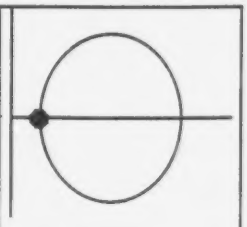
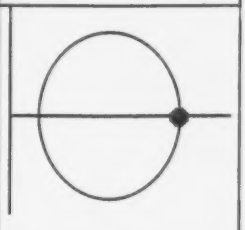
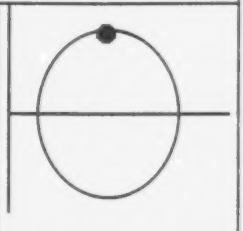
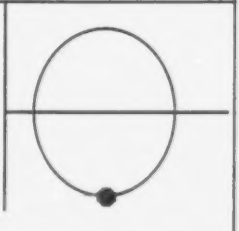
Comment: This is a good question. Is there something circular about the piston's motion? Should there be something circular about it to make a circular velocity vs. distance graph?

Victor: That's, it's going up and down like this. *[makes a back and forth motion with his finger to indicate the piston moving back and forth on the track]*

Joshua: I don't understand that.

. . .

Victor:	See this is when it's going up [*the piston is moving up the track*]. [*traces his finger along top half from 9 o'clock to 3 o'clock*] t	
	this is when it stops going up [*points to 3 o'clock*]	
	and comes down [*traces his finger along the bottom half from 3 to 9*]	
Joshua:	Oh, all right.	
Victor:	And this is, like...	
Joshua:	But why would it, what's this point right here then? [*points to 6 o'clock, the lowest point on the graph*]	
Victor:	A point, a point where the piston's going down.	
. . .		
Joshua:	The lowest point...	

Victor:	No, this is the lowest point it [the piston] gets [on the track] right here, *[points to 9 o'clock]*	
	this is the highest point it gets *[points to 3 o'clock]*	
	this is in between high and low *[points to 12 o'clock]* ,	
	that's the same this as that *[points to 6 o'clock]* but this one is decelerating [*probably meaning negative velocity*].	

Interpretive Notes

• **What is Going On?**

In a 40 second span, Victor shows a significant understanding of a velocity vs. distance graph and the relationship between shapes or points on the graph and the movement of the cart. In no particular order, Victor demonstrates to Joshua:

1) a circular shape as a graph of linear motion,

2) the graph line above the x-axis as indicative of positive velocity, the car going from the lowest point to the highest point (and vice-versa),

3) the graph line on the x-axis as indicative of the car stopping,

This is an interesting incident also because of the level of discourse. The two students are talking to each other, they are not going through the adult in the room. Joshua listens to Victor and asks thoughtful, honest questions. There is a sense, even

in this brief excerpt, that Joshua is building his knowledge. His questions show logical connections both to the question he previously asked and to Victor's answers. In the same way, Victor listens well to Joshua's questions and gives him concise, to-the-point answers.

•Interaction with the Physical Device

Throughout this excerpt, Vittorio is adept at going back and forth between the physical–the cart and piston–and the graphical representation on the computer screen. In response to a question about the graph, he gives an explanation using the motion of the piston. When his response is not understood, he gives a complete explanation of the motion using the image of the graph (he points to various points on the circle) but the language of the physical ("See, this is when it is going up [*traces his finger along the top half of the graph*]"). This explanation continues throughout, Vittorio explains the graph by referring to points on it, while describing the piston's motion at that time.

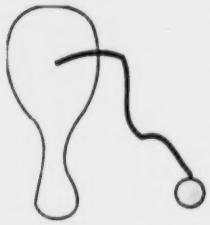
• Complexity

Joshua's questions expressed his own puzzlement at a graph that looked like a circle even though neither the car nor the piston moved in circles. Victor's explanation helped Joshua to make sense of the circle as symbolizing the motion of the piston in ways that do not resemble a simple trajectory. Victor's simultaneous talk and gesture on the graph and the device broadened the group's experience of complexity in the sense of enriching the domain of "all that goes on" with the Bouncing Car device. This experiential widening of the device's complexity gets reflected in the appearance of a new form of talk that we can distinguish from the ones that had emerged in Episodes 1 and 2. This form of talk is characterized by the following: "**This** [a point or trait in the graph] **is this** [a position or feature in the device],"whereas in the former episodes typical forms of talk can be exemplified by: "the peaks would be smaller, because, it'd be heavier" or "the heavier the weight is the more it'll, it'll move up" in which the issue is physical causality. The conversation in Episode 3 is not about physical causality but about the dual identity of graphical and physical attributes (e.g.: for the piston to be somewhere **is** for the graph to be somewhere and vice-versa).

Toward Episode 4

The 3rd interview begins with Tracy posing a challenge to the students: to adjust the device so that the piston is moving and the car bounces against it periodically, bouncing up to the same height every time (clap your hands together repeatedly and imagine one hand is the piston and the other is the car) The students claim that this is impossible, and explain why. Then they experiment with the device and try to find patterns in the aperiodic, random-seeming motions of the car that they cause. After their break, Tracy hands out ball-and-paddle toys and asks the students if they could

relate these toys to the Bouncing Car device. Victor immediately answers that the paddle is like the piston and the ball is like the car, and Terence seems to agree. Tracy then asks them if they can make the regular, periodic motion with these toys:



After experimenting with the toys for a while, they return to the device and make some additional attempts to make the car move periodically, while describing why it is impossible, and occasionally referring back to the ball-and-paddle toys. Episode 4 consists of part of this discussion, and then the event of one student finally releasing the car in such a way as to produce a periodic motion.

Summary of Episode 4

Episode 4 begins with Tracy asking whether the students believe that periodic motion might be possible for the bouncing car, now that they have created periodic motion themselves, with the ball-and-paddles. Thomas is still convinced that periodic motion for the Bouncing Car is impossible, and he explains why in detail. Victor still maintains that periodic motion is possible. Joshua eventually demonstrates this possibility, by dropping the car in such a way that it begins bouncing regularly, and periodically, alternating between two slightly different peak sizes. The group is very impressed.

[Note to the reader: This transcript section will be considerably improved for the presentation and distribution of papers at AERA.]

Episode 4 - Interview 3 (53:30 - 1:10:00)
Is it possible to make a regular, periodic, motion?

Annotated Transcript

Tracy asks the group if they think it would be possible to produce a regular, periodic motion of the car, like the regular motion they were able to produce with the ball-and-paddle toy.

Terence: What? Like going on the motion? [Tracy: Yeah.] Like always hitting the piston at this time? [Tracy: Yeah.] [*smiling*] I think it's impossible.

Tracy: You think it's impossible?

Terence: I don't know. I think you should try it.

Tracy: But it's so easy [*to produce a regular, periodic motion*] with that [*the ball-and-paddle*].

Terence: Yeah, but I'm, like, I'm doing this to control it [*demonstrates with the ball-and-paddle*]. This piston just keeps coming back and forth. Like if I don't want it to do that, I just keep on hitting it.

Tracy: How are you moving your hand to get it to do that?

Terence: Slow. [Tracy: Slow.] Just like this [*demonstrates with the ball-and-paddle*] [Tracy: Just like this?] I think you can do it [*make the regular, periodic motion with the Bouncing Car*].

Tracy: . . . Do you?

Terence: Oh, I, you know, you can't. [Tracy: You can't...] You know why? 'Cause I'm going like this [*demonstrating*], and at a point when it go to the right [*the ball*], I pull back like this [*on the paddle*].

Victor: 'Cause your body is always monitoring [*the motion of the ball and the paddle*]. If you close your eyes, you may be able to...

Tracy: That' probably when the ball can come off there [*off the paddle*].

Terence: Yeah. You can try [*with the Bouncing Car*], but I don't think it works.

Comment: Terence and Victor have been able to make relatively regular, periodic motions with the ball-and-paddle, but they realize that their bodes are making adjustments for the way the ball bounces around, to keep the paddle right under the ball and to move it at the right speed. Since the piston can't do this, it seems to them that the piston could not make the car move in this regular way.

The group then moves to the Bouncing Car device, and Terence takes the controls and tries many different settings, watching the car bounce. Tracy suggests that Terence not change the frequency of the piston's motion so quickly. Terence comments on the different positions at which the car hits the piston. Terence notices a point at which the behavior of the car seems to be regular, but then it changes.

Tracy: [to Terence] You thought it was going to be regular right there? It keeps looking like it's going to be for a second, then it's not.

Terence: I think it could happen [*regular, periodic behavior of the car*], but, like, for a little bit. Then it's going to start messing up [*becoming irregular*]. It depends on how far the car goes. The further the car moves, like if it reaches it [*the piston reaches the car*] and it's coming down [*the piston is moving down*] when the car catches it, at that point right there, when the piston is right there, it ain't going to bounce back up, 'cause it's going to come right here, stop, do a couple of bounces and then this is going to push it out. I think it'll do it [*periodic motion*], but like for a little while, but it [*the periodic motion*] won't be constant.

Tracy: [addressing Victor, Joshua] What do you guys think about what Terence says: that it's never going to be able to stay regular [*the motion if the car*]. Do you think that's true, that it won't stay regular?

Victor: I don't think it is. [Tracy: You don't think it's true?] At some point it will stay regular all the time [*permanently*].

Tracy: If it's at the right speed [*the piston's speed*]?

Victor: Yep.

Terence: Yeah, but you know why, you know why it won't happen? I think it's impossible because sometimes the car is catching it [*the piston*] when this [*the piston*] is all the way up, so it's sending it [*car*] out further, and then when it [*car*] comes down, the piston is moving, it's still moving, and it's going to catch it [*the piston*] at some point when this [*the piston*] is down there [*at the bottom of its stroke*] and then it's just going to hold it [*the car will stay and move with the piston*]. It depends on how far the car goes.

Tracy: And what determines how far the car goes?

Terence: Where it catches it. Where the car comes, like where the car and the piston meets.

Comment: Terence points out that how the car bounces depends heavily on the point in the piston's motion where the car hits it: whether the car "catches' the piston when it is "all the way up" or "down there". In Episode 1, the group concluded that the direction of motion of the piston at the time of impact determined how the car bounced, a result that he is referring to, but that he thinks of in term of the position of the piston. Whether the piston is high or low in its stroke was found by the group to actually be far less important that the direction of the piston's motion, and it can have a particular direction of motion at any point in its stroke. However, Terence also realizes that where the car hits the piston is determined by "how far the car goes" before coming back down to hit the piston, and that this is determined by what happened at the previous bounce.

. . .

Terence: I know it's impossible to have a graph that's constant.

Tracy: Well, it will really be interesting to see if that's really impossible.

Terence: It will go, like, for a while; then it will start changing.

Tracy: [to Joshua, Victor] What do you guys think? Do you think it's impossible now, or do you think it might be possible?

Terence: It's impossible.

Victor: I'm not saying it's impossible.

They do a trial and the car moves regularly for a little while, then starts moving irregularly. They discuss Terence's argument for the impossibility of a regular motion. Meanwhile, Joshua has carefully timed his drop of the car against the moving piston, and the car starts bouncing in a ***regular, periodic way****.*

Tracy: That [car motion] looks pretty good, though, or doesn't it? Look at that!

Terence: We got it.

Joshua: Everything's perfect.

Tracy: Wow.

Victor: You're proving yourself wrong, Terence?

. . .

Joshua: I dropped it [the car]. I dropped it and waited for it [piston] to go up so that it [car] would go together with the piston [move downward with the piston?].

Tracy and Joshua discuss how he dropped the car. The position vs. time graph of the motion is being drawn. There are two sizes of peaks for the car's graph, one slightly smaller than the other. The two sizes of peaks alternate with each other, keeping up a constant pattern.

Terence: That [the graph] has a pattern. That has a pattern.

Victor: Boy, look at those peaks! It has a pattern. I can see a pattern.

After Episode 4

The group allows the device to run for a long time, and the car's periodic behavior is very stable during this time, changing only when one of the wheels comes out of its groove. Terence was initially skeptical, but seemed convinced after a while that regular, stable, periodic behavior is possible. They spent some time discussing the pattern of the graph and timing of the collisions, and also demonstrating the device's behavior with the ball-and-paddles.

Interpretive Notes

• What is Going On?

This Episode begins with Terence's conjecture that a regular, periodic motion of the car and piston would be impossible. He goes on to describe in detail the way the bounce height of the car depends on the collision with the piston, and the way that the collision with the piston is related to how the car moved after the previous collision. The description he is developing of the factors affecting the car's behavior is complex in the sense that so much is going on that he believes it is impossible to know what will happen to the car next, and to get regular, periodic behavior from the car. While Terence seems to be convinced that any periodic behavior would only be a transient state, and that after a while, "it will start changing," Victor seems convinced that settling into regular behavior is inevitable: "At some point it will stay regular all the time." Everyone is surprised when Joshua, who has been quiet for this discussion, produces regular behavior by carefully timing his drop of the car against the moving piston. The visibly regular behavior of the car and the extremely clear pattern on the peaks on the graph seemed to impress the students, and they were anxious to understand the pattern in the graph.

•Interaction with the Physical Device

In this episode, the group's interaction with the Bouncing Car device was influenced by Tracy's introduction of the ball-and-paddle toys, which she explicitly asked the students to relate to the Bouncing Car. When Tracy asked them to produce with the ball-and-paddle toys a regular, periodic behavior that she later asked them to produce with the Bouncing Car, the students' experience with the toys became a new resource to draw on to explain what would happen with the Bouncing Car. In the quotes below, Terence and Victor argue that the piston can't make the car move periodically, because it can't do what they have to do with their bodies to make the regular, periodic motion of the ball on the paddle:

Terence: Oh, I, you know, you can't [*make the car move regularly*]. [Tracy: You can't...] You know why? 'Cause I'm going like this [*demonstrating*], and at a point when it go to the right [*the ball*], I pull back like this [*on the paddle*].

Victor: 'Cause your body is always monitoring [*the motion of the ball and the paddle*]. If you close your eyes, you may be able to...

They are relating their physical experience with moving the paddle to the piston, but the piston can not do what their bodies can do. This is another example of the students putting themselves in the place of the piston, imagining the motions of their hands holding the paddles to be those of the piston, expect in this case they realize that they have gone beyond the limits of what is possible for the piston.

• Complexity

In this episode, we hear a very different story told than the one we heard in Episode 1. In Episode 1, the students described the results of the car hitting the piston during different parts of its stroke, and we saw evidence that they felt this behavior to be obvious and self-evident. In Episode 2, they began to take many factors into account in their discussion of the effect of the weight on the bounce height of the car, but they still expected to find one relatively clear answer from their experiments. In Episodes 2 and 3, we also see the development of a complexity in the students' descriptions of the device's behaviors, which expand to include various kinds of graphs of its motion that the motion detector produces. Then in Episode 4, when Tracy ask the students if they can produce a regular, periodic behavior of the car over many cycles of the piston, Terence begins to describe his belief that the multiple influences on the car's behavior that the group has explored in earlier interviews should interact to make the car's behavior tend inevitably to randomness. On the scale of the car's behavior over many minutes, Terence believes this system is so complex that its behavior can not be determined. Although the group proves to Terence that regular behavior is possible, his experience of the complexity of this system and its connection to randomness is an important insight about the behavior of this device that emerged slowly over the course of these three interviews.

Conclusions

On the Interaction with Physical Devices

The students approached the Bouncing Car device by striving to imagine their *being* parts of it, such as being the car or the piston. Their efforts to figure out what it is like to be the car or the piston focused on gestural actions (e. g.. moving the hands as of they were the car and the piston) and metaphorical accounts (e.g. Joshua's sled as being the car). This identification of themselves with elements of the device offered them *entry points* into their growing making sense of the Bouncing Car behavior. These observation suggests to us the conjecture that an important contribution of students' interaction with physical devices, such as the Bouncing Cart, is to enrich their reflection on the everyday bodily experience. After all, the device is subject to the same forces and gravitational constraints of a human body. As opposed to a simulation, which is a manifestation of a logical-mathematical model of the bodily experience confined to the flat surface of the computer screen, the Bouncing Car device manifests the physical world in which all of us are immersed and opens up a wide domain of gestural appropriation of its behavior (e.g. seeing it from different angles, following its motion with one's hands, etc.). This is not argument against the use of simulations, which have their own merits, but against using simulations *to replace* the interaction with physical devices .

On Complexity

The experience of complexity in the sense of "there is so much going on in this device" and "there are so many ways to think about this device" seems to us a crucial learning experience. Across the four episodes we have traced the growth of students' sense of complexity. This growth was based on their exploration of multiple entry points (e.g. the effect of weight in how far the car goes up, the different ways in which the car hits the piston, and so forth), their emergent awareness of the dual identity of graphical and physical attributes (e.g.: "the peaks will get smaller;" "a point where the piston's going down," etc.), and the constant involvement of their gestural and metaphorical body actions. This development supports the notion that complexity or simplicity are not "in the device" but in students experience with the device, and that complexity is not a given but an outcome of the active participation in the conversation about and experimentation with the tools at hand.

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